

Extragalactic relativistic jets

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Abstract

Extragalactic relativistic jets are engines able to carry out to large distances a huge amount of power, not only in the form of radiation, but especially in the form of kinetic energy of matter and fields. As such, they can be thought as one of the most efficient engines of Nature, perhaps even more efficient than accretion. We are starting to disclose these features through a detailed study of their properties, made possible by the analysis of the energy band where they emit most of their electromagnetic output, namely the γ -ray band. That is why the observations by the *Fermi* satellite and by the ground based Cherenkov telescopes are crucial to understand extragalactic jets. At the start, we believe they are magnetically dominated. And yet, on the scale where they emit most of their luminosity, their power is already in the form of kinetic energy of particles. The spectral properties of bright sources show a trend, controlled mainly by the bolometric apparent luminosity. With improved sensitivity, and the detection of weaker sources, we can explore the idea that the spectral trends are a result of the same physical quantities controlling the emission of non-jetted sources: the black hole mass and the accretion rate. This is based on recent results on sources showing a thermal component in their spectrum, besides a non-thermal continuum. That the jet power should be linked to accretion is intriguing. Most of the apparent diversity of extragalactic radio sources can then be understood on the basis of the viewing angle, controlling the relativistic Doppler boosting of the emission, the black hole mass and the accretion rate.

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gamma-ray, blazars, accretion disks, jets

1 Introduction

We now know that almost every galaxy hosts a supermassive black hole, from millions to billions of solar masses. The vast majority of them is “silent”, but about 1% of them accretes enough matter to become visible and overtake the emission from the ensemble of stars in the entire galaxy. About 10% of these systems, thus 0.1% of the supermassive black holes, is able to launch relativistic jets. These jets design spectacular structures in the radio, with sizes far exceeding the dimensions of the host galaxy, reaching in a few cases the megaparsec scale. The emitting matter is moving relativistically, with bulk Lorentz factors $\Gamma > 10$ (i.e. $\beta > 0.995$), therefore boosting the emission in a cone of semi-aperture $1/\Gamma < 5^\circ$. Objects seen face on are dramatically different from objects observed from the side. The former are called “blazars” (BL Lac objects and flat spectrum radio quasars, or FSRQs for short). The latter are radio-galaxies. Because of the relativistic boosting, blazars are powerful, active, rapidly variable and detectable from the farthest distance.

Although first discovered in the radio, jets do not emit much in this band. They instead emit most of their radiation at the other extreme of the electromagnetic spectrum, namely in the γ -ray band. This is why we had to wait the launch of the *Compton Gamma Ray Observatory*, *CGRO* and its EGRET instrument [0.1–30 GeV] to discover that all blazars were strong γ -ray emitters as a class (Hartman et al. 1999; Nandikotkur et al. 2007). At last we could know the bolometric luminosity and the entire spectral energy distribution. This turned out to be double humped. The first hump is interpreted as synchrotron emission. The second, high energy, one is usually interpreted as inverse Compton (IC) emission (but there are other suggestions, see Mannheim 1993; Mücke et al. 2003; Böttcher 2007; Aharonian 2000; Mücke & Protheroe 2001).

The apparent γ -ray luminosity (calculated assuming isotropy) can be huge, exceeding for a few days 10^{50} erg s $^{-1}$ (left panel and right y-axis of Fig. 1; see also Abdo et al. 2011). Coordinated variability of the flux at different frequencies (belonging to the two humps; Bonnoli et al. 2011; see the right panel of Fig. 1) implies two important facts: i) the same population of leptons is responsible for both humps and therefore ii) there must be a single emitting zone.

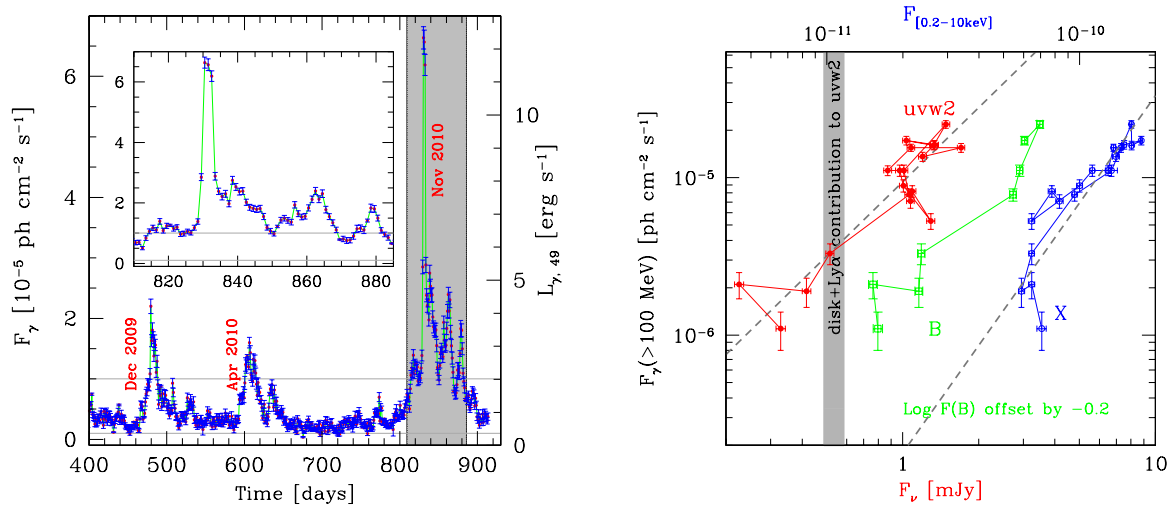


Figure 1: **Left:** Light curve of 3C 454.3 in the γ -ray band of *Fermi*/LAT showing three major flares. Time bins are 1 day. The inset is a zoom of the last one, occurred in November 2010. Time bins are 1 day long. Assuming that the 0.1–10 GeV spectrum is a power law of energy index $\alpha_\gamma \sim 1.2$, we can calculate the corresponding luminosity (assuming isotropy), that exceeded 10^{50} erg s $^{-1}$ in Nov. 2010. Note also the fast variability. A detailed analysis showed a variability timescale (i.e. the time to halve or double the flux) of a few hours (Tavecchio et al. 2010; Foschini et al. 2011). **Right:** Correlation between the γ -ray, the X-ray and the UV flux of 3C 454.3 during the Dec. 2009 flare (from Bonnoli et al. 2011).

There is still some discussion about the origin of the seed photons that are scattered at higher energies: these could be the synchrotron photons produced internally to the jet (synchrotron self-Compton process, SSC; Maraschi, Ghisellini & Celotti 1992; Bloom & Marscher 1996), or else photons produced outside the jet (and in this case the process is called External Compton, EC). In fact, at least in powerful blazars, there are several important photon sources: radiation coming directly from the accretion disk (Dermer & Shlickeiser 1993), or re-isotropized by the clouds producing the broad emission lines (Sikora, Begelman & Rees 1994); IR radiation produced by a dusty torus surrounding the accretion disk (and extending to a few parsecs from it; Sikora et al. 2002).

At some level, all these photon sources contribute, with a relative weight that is dependent upon the distance of the emitting region from the black hole (Ghisellini & Tavecchio 2009). But since BL Lac objects have weak or absent emission lines, the EC process in these objects should be less important. On the contrary, FSRQs with broad emission lines similar to radio-quiet objects (of similar disk luminosity) should have more seed photons to scatter, and thus produce a relatively stronger high energy hump. Although some exceptions exist, this is what we see, and this is at the core of the explanation of the so called “blazar sequence”: a well defined trend between the overall spectral shape (or spectral energy distribution, SED) and the apparent bolometric luminosity of blazars (Ghisellini et al. 1998). Fig. 2 shows that at low luminosities the SED of blazars (mostly BL Lac) peaks at large frequencies (synchrotron hump: opt–UV–soft X–ray, high energy hump: GeV–TeV). The two humps have similar luminosities. Increasing the bolometric power, the SED shifts to smaller frequencies, and the high energy hump prevails. Fig. 2 shows, as lines, the phenomenological SEDs originally derived by Fossati et al. (1998) and Donato et al. (2001) on the basis of complete sample of blazars selected at radio or X–ray frequencies. Blazars detected in the γ -ray range were very few. It is interesting therefore to compare these early representation of the blazar sequence with the bright blazars detected by *Fermi* in the 3 months all sky survey (LBAS catalog: Abdo et al. 2009), divided into γ -ray luminosity bins. We can see that the solid lines represent rather well the average SEDs, but tend to over-predict the high energy flux at intermediate γ -ray luminosities (red and green lines). This can be due to the fact that *Fermi*, ~ 20 times more sensitive than EGRET, starts to observe blazars not only in their high states, but also when they are not extremely active.

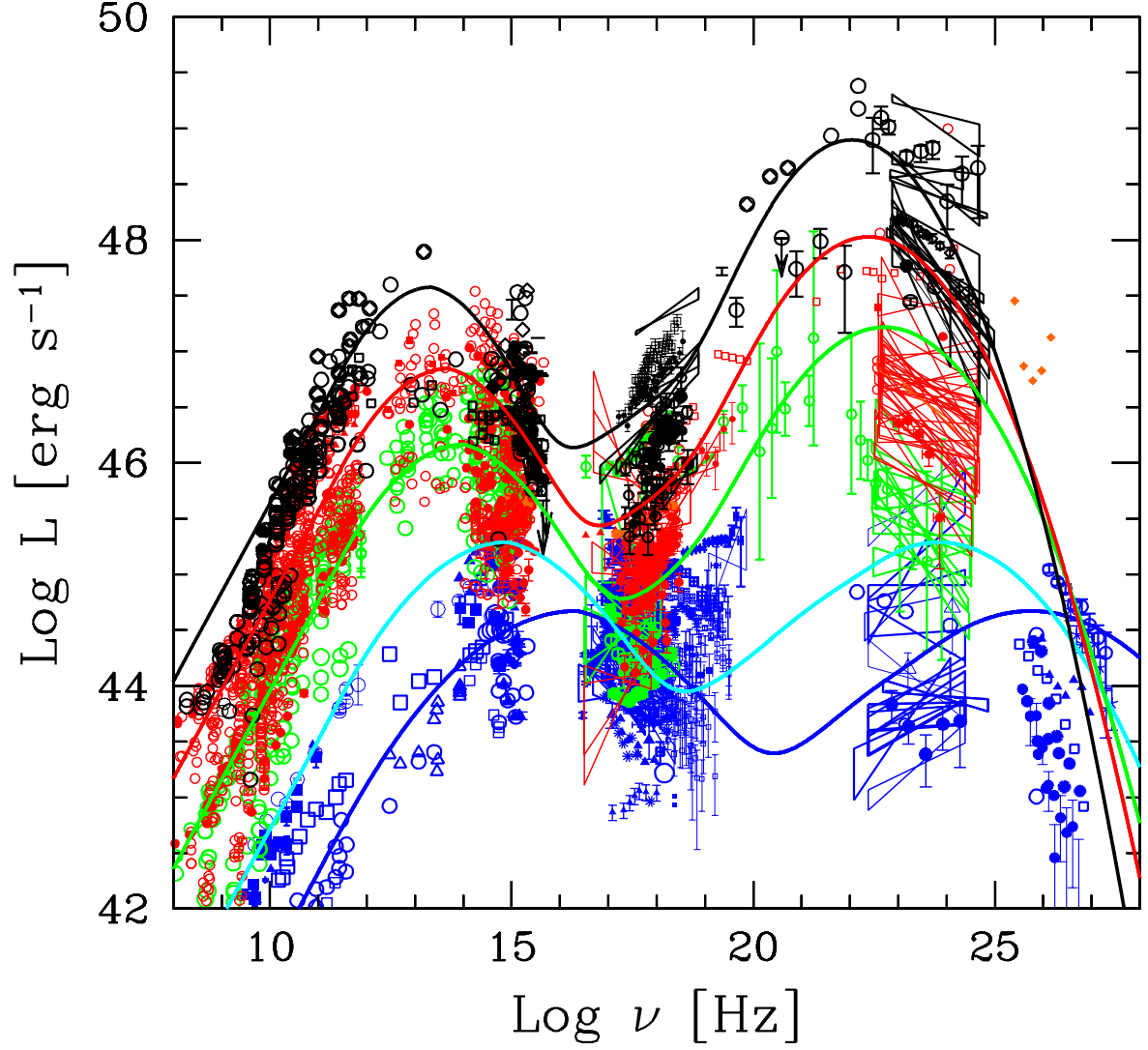


Figure 2: The blazar sequence. Solid lines are the phenomenological SED supposed to describe the SED of blazar of different bolometric luminosities, according to Fossati et al. (1998) and Donato et al. (2001). The data are the SED of real sources detected in the first 3 months of survey by the *Fermi* satellite (LBAS catalog: Abdo et al. 2009), divided (different colors) into bins of different γ -ray luminosities in the [0.1–10 GeV] range: $\log L_\gamma < 45.5$ (blue), $45.5 < \log L_\gamma < 46.5$ (green), $46.5 < \log L_\gamma < 47.5$ (red), $\log L_\gamma > 48.5$ (black).

2 TeV BL Lacs

At the low luminosity end of the blazar sequence we find BL Lacs whose synchrotron spectrum peaks in the UV or soft X-rays (and sometimes even in the hard X-ray band, as in Mkn 501; Pian et al. 1998), and the high energy hump extends to the TeV band. In the *Fermi* band they are relatively weak, but hard (i.e. energy spectral indices $\alpha_\gamma < 1$). The interest of these objects¹ concerns three main aspects:

- Since the emitting electrons reach TeV energies, they give information about the acceleration mechanism at its extreme. Particularly challenging in this respect are the ultrafast variations seen in PKS 2155–304 (Aharonian et al. 2007) and in Mkn 501 (Albert et al. 2007), showing a doubling of the TeV flux in about 3–5 minutes. The causality argument, implying $R < ct_{\text{var}}\delta$ where δ is the Doppler factor (Begelman, Fabian & Rees 2008), means that such small t_{var} cannot be any longer indicative of the size of the black hole (as instead is in the “internal shock scenario” (Sikora et al. 1994; Ghisellini 1999; Spada et al. 2001; Guetta et al. 2004). The proposed solutions suggest that the emitting region responsible for the ultrafast variations has a dimension much smaller than the cross sectional radius of the jet, moving with a very large bulk Lorentz factors. This can be produced by small reconnecting regions (Giannios et al. 2009a; “jet in the jet” model) or “needles” of emitting leptons (Ghisellini et al. 2009) very aligned with the line of sight.
- Since the TeV photons can be absorbed by the $\gamma\text{--}\gamma \rightarrow e^\pm$ process interacting with the cosmic IR background, they can give information about the latter (e.g. Mazin & Raue 2007). Using GeV (i.e. *Fermi*) and TeV (i.e. Cerenkov telescopes) data greatly helps to estimate the amount of the absorption (important above a few hundred GeV).
- The electron–positron pairs created by the above process have \sim TeV energies and can scatter photons of the cosmic microwave background (CMB) up to \sim GeV energies. In the absence of any intergalactic magnetic field B this reprocessed flux must be equal to the absorbed one. However, if a magnetic field is present, the pairs start to gyrate while cooling, spreading their reprocessed flux in a broader beaming cone. As a result, the received reprocessed flux is less than in the $B = 0$ case. Therefore the knowledge of the absorbed TeV flux together with the GeV one gives an indication of B . Since the received GeV flux can be the sum of the reprocessed radiation and the flux intrinsically produced by the source, what is derived is a lower limit on B (Neronov & Vovk ; Tavecchio 2010; see Dermer et al. 2011 and Tavecchio et al. 2011 for some caveats about the use of this method).

3 The Blazars’ divide

The blazar sequence predicts that the high energy hump peaks at a frequency that shifts to smaller values by increasing the bolometric apparent luminosity. This is a simplification for several reasons. First, the sources do vary, especially in the γ –ray band, by huge factors (i.e. even more than two orders of magnitude). Second, the use of the apparent luminosity depends on the level of Doppler boosting (therefore on the viewing angle). Sources very powerful when viewed on axis becomes much fainter at larger viewing angles θ_v (i.e. there is a factor ~ 16 going from $\theta_v = 0$ to $\theta_v = 1/\Gamma$). Therefore a blazar that appears powerful on axis becomes much weaker if seen –say– at 10° , with a high energy peak that is shifted to smaller values (e.g. contrary to what naively expected from the blazar sequence). Note that these objects *must* exist. Third, blazars with different black hole masses are expected to have different jet luminosities (Ghisellini & Tavecchio 2008) but an overall SED controlled by the Eddington ratio (e.g. for smaller black hole masses the jet luminosity could be smaller, but the two humps should peak at small frequencies).

Given all these caveats, one may wonder why the blazar sequence does work at all. Most likely, the answer is in the fact that we are still detecting, in the γ –ray band, the tip of the iceberg of a much broader distribution of properties. In γ –rays we still detect the brightest sources, that are the most aligned and with a greater black hole mass.

This explains why, for the brightest *Fermi* blazars detected at more than 10σ confidence level in the first three months of operations, there is a relation between α_γ and L_γ , with a relatively well defined

¹see <http://www.mpp.mpg.de/~rwagner/sources/> for an updates list of TeV detected blazars.

“divide” in luminosity ($L_\gamma \sim 10^{47} \text{ erg s}^{-1}$) between BL Lacs and FSRQs (see Fig. 1 in Ghisellini, Maraschi & Tavecchio 2009). The most luminous FSRQs reach $L_\gamma \sim 10^{49} \text{ erg s}^{-1}$. By assuming that i) all these blazars have the same mass; ii) the same Doppler boosting and iii) there is a proportionality between L_γ and the accretion luminosity L_d , we have suggested that this factor ~ 100 corresponds to a factor 100 in L_d . Assuming further that the greatest L_γ occur in systems with $L_d/L_{\text{Edd}} \sim 1$, we conclude that the BL Lac phenomenon occurs in systems with accretion disk radiating at a $L_d/L_{\text{Edd}} < 10^{-2}$ level. This long chain of arguments may seem somewhat contrived at firsts, but all steps can be (and have been) verified by more detailed analysis (and information), and we can now confirm this important conclusion: the accretion rate (in Eddington units) controls if a blazar is a low power and lineless BL Lac or a powerful and line emitting FSRQ. Using completely different arguments, Ghisellini & Celotti (2001) reached the same conclusion for the two types (FR I and FR II) of radio-galaxies, that are thought to be the parent population of blazars.

We may wonder what happens when we start to include, in the α_γ - L_γ plane, the (fainter) blazars detected in the first 11 month of *Fermi* life, with a $> 5\sigma$ confidence level. These are shown in Fig. 3. There is still a “zone of avoidance” for flat and powerful sources (although there is still a concern about blazars with no lines and then no redshift that could populate this zone if their redshift is larger than 2), but the “divide” in L_γ , that was clear in Fig. 1 of Ghisellini, Maraschi & Tavecchio (2009), is now absent. We suggest that this is because of the reasons outlined above: we start to see objects not perfectly aligned, possibly with smaller black hole masses and then smaller L_γ , yet with the same Eddington ratios than before. Fig. 3 shows lines of increasing $\dot{M}/\dot{M}_{\text{Edd}}$ for different black hole masses M , that can encompass the data points.

3.1 Different accretion regimes for BL Lacs and FSRQs

The found “divide” for BL Lacs and FSRQs (and FR I and FR II radio-galaxies) can have a simple and straightforward interpretation if there is a change in the accretion regime, going from radiatively efficient (for large \dot{M} and L_d) to radiatively inefficient (Narayan Garcia & McClintock 1997). This change is expected to occur around $L_d/L_{\text{Edd}} \sim 10^{-2}$, corresponding to $\dot{M}/\dot{M}_{\text{Edd}} \sim 0.1$ (here $\dot{M}_{\text{Edd}} \equiv L_{\text{Edd}}/c^2$, without considering the efficiency of accretion).

When radiatively inefficient, the spectral shape of the disk is very different from what produced by a standard (i.e. Shakura & Sunjaev 1973) disk in two respects: i) the accretion efficiency η defined as $L_d = \eta \dot{M} c^2$ becomes a function of \dot{M} , decreasing for decreasing \dot{M} . Narayan, Garcia & McClintock (1997) proposed $\eta = \min(0.1; \dot{M}/\dot{M}_{\text{Edd}})$. ii) the fraction of the bolometric luminosity emitted in the optical UV decreases, so that the ionizing flux decreases even more than linearly with \dot{M} . The decreased ionizing flux means that all the broad lines becomes weaker: we have a BL Lac object. The decreased amount of seed photons for the IC process implies a weaker radiative cooling for the relativistic electron in the jet, and they can thus reach larger typical energies: therefore the two humps peak at larger frequencies. The high energy hump is mainly produced by SSC only, and is thus less dominant (or even weaker) than the synchrotron hump. These arguments explain the general properties of the blazar sequence.

3.2 A new classification of blazars

Traditionally, blazars are classified as BL Lacs or FSRQs according to the equivalent width (EW) of their broad emission lines (see e.g. Urry & Padovani 1995). Objects with a rest frame $\text{EW} < 5 \text{ \AA}$ are called BL Lacs. This definition has the obvious advantage of being simple and of immediate use for an observational characterization of the object, and it does measure the relative importance of the beamed non-thermal continuum in the optical band. On the other hand, EW greater than 5 \AA may be the results of a particularly low state of the beamed continuum in a source of intrinsically weak lines. On the opposite side, in several cases a small EW does not imply emission lines of low luminosity, being simply the result of a particularly beamed non-thermal continuum. PKS 0208–512 can illustrate this point: it has an observed MgII emission line of $\text{EW} \sim 5 \text{ \AA}$ (2.5 \AA in the rest frame; Scarpa & Falomo 1997), whose luminosity is close to $10^{44} \text{ erg s}^{-1}$, stronger than in some FSRQs. This object is classified as a BL Lac, but all its physical properties are resembling FSRQs. When discussing the different physical properties of BL Lacs and FSRQs it is then confusing having sources like PKS 0208–512 classified as a BL Lac. We (Ghisellini et al. 2011)

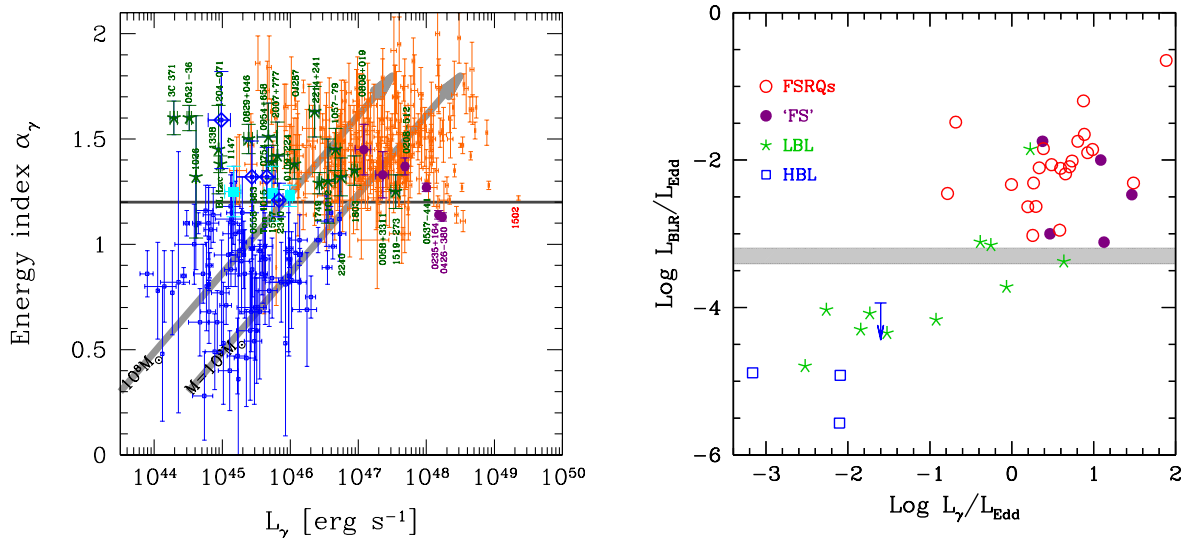


Figure 3: **Left:** The energy spectral index α_γ as a function of the γ -ray luminosity L_γ in the band [0.1–10 GeV] for all blazars with known redshift present in the 1LAC sample (Abdo et al. 2010a). Note that some BL Lacs are in the “FSRQ” region, characterized by a steep slope ($\alpha_\gamma > 1.2$). These “intruders” have been partly re-classified as FSRQs by Ghisellini et al. (2011) on the basis of the luminosity of their broad emission lines, measured in Eddington units (filled violet circles). **Right:** Luminosity of the broad line region (in units of the Eddington one for sources with at least one broad line in their spectrum and with an estimate of the black hole mass) as a function of the γ -ray luminosity in units of the Eddington one. From Ghisellini et al. (2011).

have then proposed a new and physically based classification scheme. It is based on the luminosity of the BLR, measured in Eddington units. Although this study dealt with a relatively small sample of sources (all detected by *Fermi*), we found that $L_{\text{BLR}}/L_{\text{Edd}}$ correlates with L_γ/L_{Edd} (see Fig. 3) and with the shape of the SED. Due to this continuity of properties, it can even become questionable the very need to divide blazars into sub-categories. But if we really want to divide FSRQs from BL Lacs, we propose that $L_{\text{BLR}}/L_{\text{Edd}} \sim 10^{-3}$ (or slightly less) is the dividing value. This is in very good agreement with what discussed before if the BLR reprocesses $\sim 10\%$ of the accretion disk luminosity: in this case the dividing disk luminosity is of the order of $L_d/L_{\text{Edd}} \sim 10^{-2}$.

4 Black hole masses and accretion

Fig. 4 (left panel) shows the SED of the *Fermi* detected FSRQ 0227–369 ($z=2.115$), together with the one-zone synchrotron+IC model used to fit the data. Fig. 4 shows that in these high redshift powerful blazars the non-thermal beamed jet continuum leaves the optical–UV disk emission unhidden. By assuming that the emission is produced by a standard Shakura–Sunjaev (1973) disk we can estimate both the black hole mass and the accretion rate. This is the case for the majority of powerful *Fermi* detected blazars, characterized by a relatively steep slope in the GeV energy range and a corresponding steep synchrotron spectrum above the peak, occurring in far IR or sub-mm range.

The main uncertainty on the derived black hole mass (if the disk can be indeed described by a Shakura–Sunjaev model) lies in the amount of absorption of the optical–UV data, affected by the intervening Lyman- α systems along the line of sight (if the blazar are at $z > 2$). In Ghisellini et al. (2010b) we have accounted for this effect, estimating the *average* number intervening of Lyman- α systems and their optical depth. The variance around the average can however be large, and this is the main cause of uncertainty. On the other hand, this method is in any case competitive with the estimates derived through the FWHM of the broad emission lines and assuming a relation between the size of the BLR and the luminosity of the ionizing continuum (Kaspi et al. 2007; Bentz et al. 2008). In fact, in Fig. 4 (right panel) we compare the

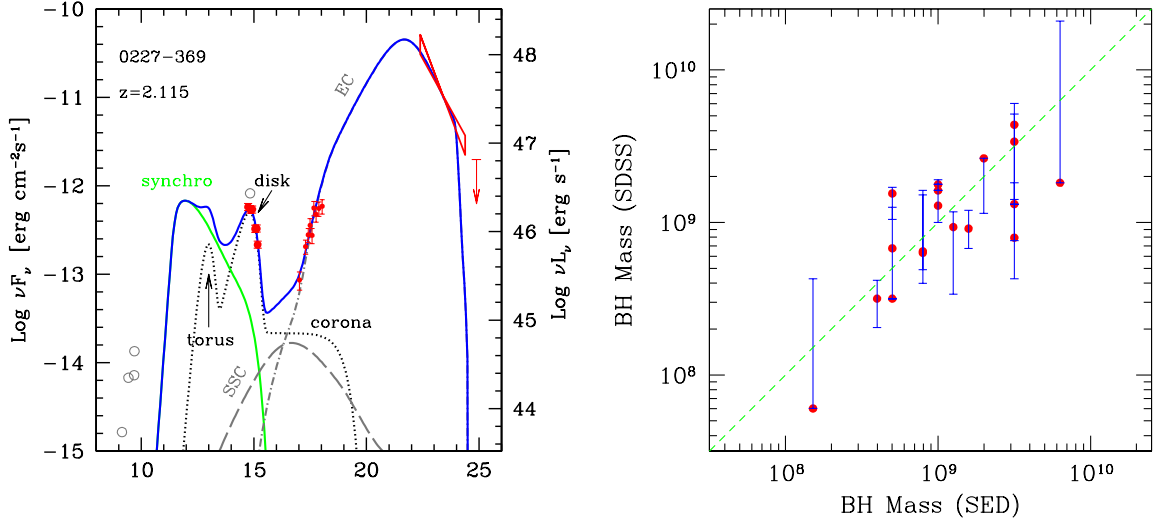


Figure 4: **Left:** The SED of the blazar 0227-269 ($z = 2.115$) modelled with the one-zone leptonic model described in Ghisellini & Tavecchio (2009). The different components are labelled. As can be seen, the non thermal jet emission, although largely dominating the bolometric output, leaves the disk emission “naked”. **Right:** Black hole masses estimated through the FWHM of the broad emission lines and the correlation between the ionizing luminosity and the size of the BLR (as calculated for FSRQs in the SDSS DR7 catalog) vs the black hole masses derived from fitting the optical-UV continuum with a simple Shakura & Sunjaev (1973) disk model. The vertical bars are not error bars, but indicate the range of minimum/maximum black hole masses estimated using different lines. The dashed line indicates equality.

black hole masses estimated by fitting the optical-UV SED with the masses derived through the emission lines. The vertical bars are not error bars, but indicate the range of masses resulting by using different emission lines and/or different scaling relations between R_{BLR} and the ionizing luminosity. The agreement between the masses calculated with the two methods is reassuring.

The left panels of Fig. 5 shows the distribution of black hole masses for two samples of blazars lying at $z \geq 2$: the left top panel refers to all blazars detected by *Fermi* present in the 1LAC catalog (A10), the bottom panel concerns all blazars detected by *Swift*/BAT (in the 15–55 keV range; Ajello et al. 2009). Almost all have $M > 10^9 M_\odot$, with the “record holder” blazar 0014+813 having $M = 4 \times 10^{10} M_\odot$ (right panel in Fig. 5). This outrageous large mass comes, formally, from the large IR–optical luminosity, exceeding $10^{48} \text{ erg s}^{-1}$, interpreted as accretion luminosity close to the Eddington limit (Ghisellini et al. 2009). Note the luminosity and slope of the IR emission, which is insensitive to absorption. The derived black hole mass in this blazar is so large to motivate the search for other explanations. One hint can come from the not so extraordinary jet luminosity: comparing 0014+813 with other BAT or LAT detected blazars at high redshift, we find that in 0014+813 the ratio between the non-thermal and the disk luminosity is a factor ~ 10 less than the other blazars. This suggests that in this specific object, emitting very close to Eddington, the accretion disk may not be geometrically thin in its inner part, but it may have developed a doughnut shape. This would make the disk emission not isotropic, but collimated along the normal to the disk. Viewing the source face on (as we do in this case, since we selected it as a blazar) we receive a larger than average flux (see Fig. 7: 0014+813 is the source with the largest L_d).

5 Jet powers

Measuring the jet power is not an easy task, since the radiation we see is beamed relativistically, and what we see does not immediately correspond to what it is produced. There are however many ways to measure the jet powers:

- Extended radio emission and/or radio lobes are a sort of calorimeters: since the radiative cooling times are long for these structures, they transform the received jet power into magnetic, electron

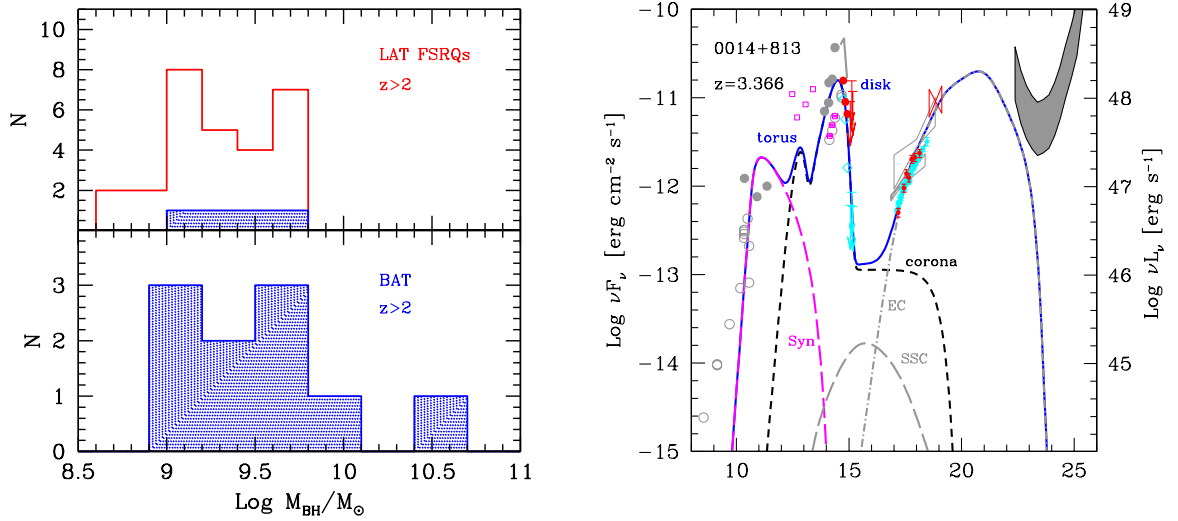


Figure 5: **Left:** Black hole mass distribution for blazars at $z > 2$ in the *Fermi* 1LAC (above) and *Swift*/BAT (bottom) catalogs. The hatched area in the top histogram corresponds to blazars in common. Almost all these distant blazars have black holes with masses exceeding $10^9 M_\odot$. **Right:** SED and model of the BAT detected blazar 0014+813. The black hole mass in this blazar is found to be around 40 billion solar masses, with an accretion rate close to Eddington. Note that the optical luminosity produced by the accretion disk exceeds $10^{48} \text{ erg s}^{-1}$. From Ghisellini et al. (2009).

and possibly proton energies. Knowing the size, and using minimum energy (i.e. equipartition) arguments (Burbidge 1959), one can find a lower limit to the jet power, that heavily depends on the assumed proton energy. Furthermore, if one can estimate the time needed to form the radio lobe, one derives the average power received by the lobe, i.e. the average jet power. This quantity correlates with the luminosity of the narrow emission lines, that should in turn be a good proxy for the accretion disk luminosity. It turns out that the average jet power and the disk luminosity calculated in this way are approximately equal (Rawlings & Saunders 1991).

- Detailed X-ray imaging of radio sources revealed the presence of “X-ray cavities” (e.g. Allen et al. 2006; Balmaverde et al. 2008) filled instead with relativistic radio-emitting electrons. One can calculate the PdV work to form these cavities and then guess the associated jet power.
- In the VLBI zone we can measure both the size of the emitting knot and its velocity, often superluminal. From the radio flux and size one can predict the amount of self-Compton emission, expected in the X-rays. Comparing with real data one derives a limit to the beaming factor. This in turn helps in fixing the required number of relativistic electrons and magnetic field needed to account for the radio emission we see, and thus the kinetic and Poynting flux of the jet.
- At the scale of hundreds of kpc, some jets have been detected and resolved in X-rays by the *Chandra* satellite (see e.g. Schwartz et al. 2000 for PKS 0637–752). This emission, interpreted as IC off photons from the microwave background, can give an estimate of the jet power (see Celotti et al. 2001; Tavecchio et al. 2000; Georgantopoulos et al. 2005)
- The bulk of emission of blazars is emitted in γ -rays. This translates in a lower limit to the jet power (it must have more power than the one radiated). The limit is (see Celotti & Ghisellini 2008)

$$P_j > P_r = \frac{L_{\text{obs}}}{\Gamma^2} \quad (1)$$

It is a lower limit because if the jet spent all its power to produce radiation, then it would stop. In powerful sources dominated by the EC process, the emission is anisotropic also in the comoving frame, therefore the jet recoils, unless the inertia of the jet is large. If the jet were composed only by

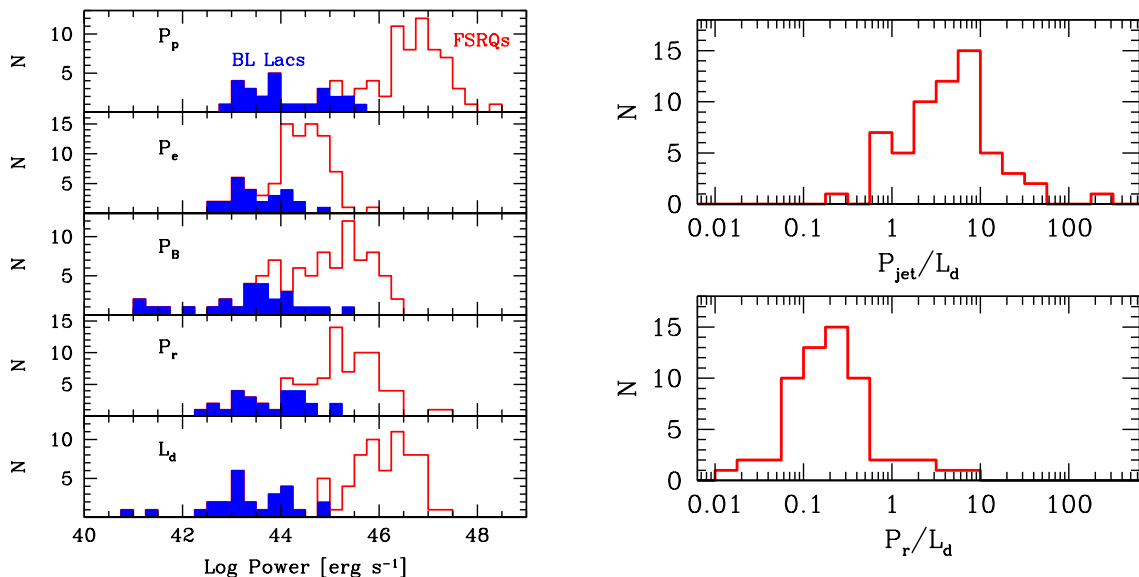


Figure 6: **Left:** Distribution of the jet power in different forms (first 4 panels) and of the accretion luminosity (bottom panel). The blue hatched areas refer to BL Lac object, the red histograms refer to FSRQs. The values for the accretion luminosity for BL Lacs are upper limits. **Right:** Distributions of P_{jet}/L_d (top) and of P_r/L_d (bottom) for FSRQs only. From G10.

e^\pm , it would decelerate strongly, so we require the presence of at least one proton every ~ 10 leptons (Ghisellini & Tavecchio 2010). They contribute to the jet power. Therefore a very robust lower limit to the total jet power is $P_{\text{jet}} > 2P_r \sim 2L_{\text{obs}}/\Gamma^2$.

Concerning the latter method, several attempts have been done in the past to find the jet power and the accretion disk luminosity in blazars and radio-loud objects in general (starting from Rawlings & Saunders 1991; Celotti et al. 1997; Cavaliere & D’Elia 2002; Maraschi & Tavecchio 2003; Padovani et al. 2003; Sambruna et al. 2006; Allen et al. 2006; Celotti & Ghisellini 2008; Ghisellini & Tavecchio 2008; Kataoka et al. 2008; Ghisellini et al. 2010a (G10); Bonnoli et al. 2011). These works found large jet powers, often larger than the luminosity produced by the disk.

The main uncertainty when estimating the power in this way is the contribution of protons to the bulk kinetic power. If one assumes one proton for each emitting electron, then the number of protons depends on the low energy cut-off of the electron distribution (where most of the electrons are), that in powerful sources is bound to be at small energies, because the radiative cooling is severe. In addition, there might be e^\pm pairs, that would limit the required number of protons and thus lower the total jet power. But, as mentioned above, the number of pairs cannot be larger than ~ 10 per proton, otherwise the “Compton rocket” recoil effect becomes too strong. This is in agreement with Sikora & Madejski (2000) and Celotti & Ghisellini (2008), who also argued that e^\pm pairs cannot be dynamically important, corresponding to a limit of a few pairs per proton.

Fig. 6 shows the histograms of the different forms of power carried by the jet. The shaded areas correspond to BL Lacs. Besides the power spent to produce the radiation we see (P_r), the power is carried in the form of relativistic electrons (P_e), magnetic field (P_B), or cold protons (P_p). All these powers can be calculated through:

$$P_i = \pi R^2 \Gamma^2 c U'_i \quad (2)$$

where R is the size of the emitting blob, assumed to be equal to the cross sectional radius of the jet, and U'_i is the (comoving) energy density of the i_{th} component of the power.

As mentioned, the most robust, almost model-independent, lower limit to the jet power is P_r , spent by the jet to produce its radiation. For FSRQs, the distribution of P_r extends to larger values than the distribution of P_e . The distribution of P_B is at slightly smaller values than the distribution of P_r , indicating that the Poynting flux cannot be at the origin of the radiation we see. As described in Celotti & Ghisellini

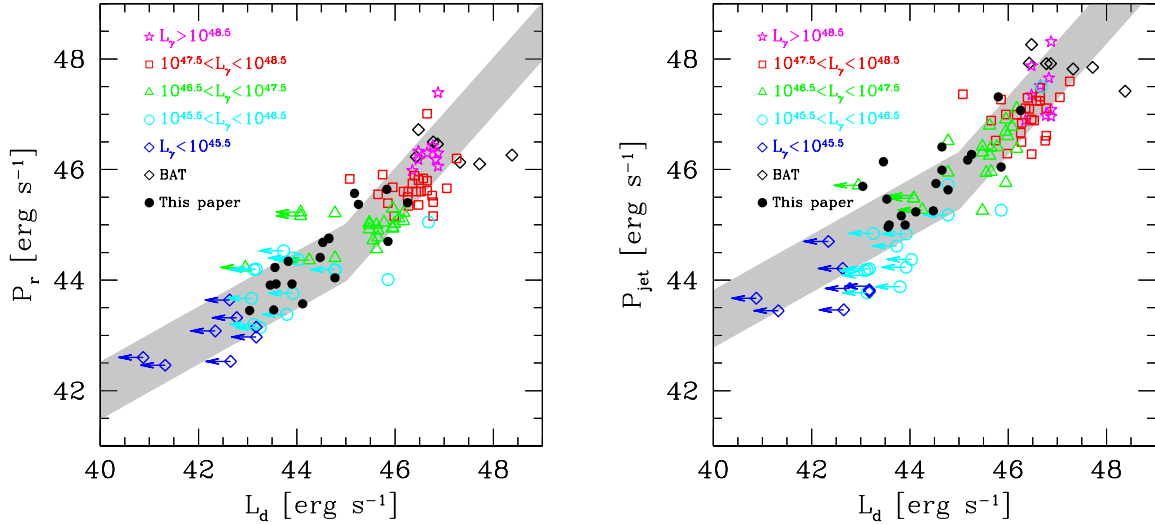


Figure 7: **Left:** Power of the jet spent in the form of radiation P_r as a function of the accretion luminosity L_d . Black symbols are the estimates in Ghisellini et al. (2011), BAT points (grey diamonds) come from the high-redshift blazars present in the 3 year all sky survey of BAT (and studied in Ghisellini et al. 2010a), the other points and upper limits come from G10, and are divided according to their γ -ray luminosities, as labelled. **Right:** total jet power P_{jet} as a function of L_d . One proton per emitting electron is assumed. The grey stripes indicates what expected if $P_{\text{jet}} \propto P_d \propto \dot{M}$ for all luminosities, while $L_d \propto \dot{M}^2$ and $L_d \propto \dot{M}$ at low and high values of \dot{M} , respectively. Therefore, for low L_d , we expect $P_{\text{jet}} \propto P_r \propto L_d^{1/2}$, while, for large L_d , we expect $P_{\text{jet}} \propto P_r \propto L_d$.

(2008), this is a direct consequence of the large values of the Compton dominance (i.e. the ratio of the Compton to the synchrotron luminosity is small), since this limits the value of the magnetic field.

To justify the power that the jet carries in radiation we are forced to consider protons. If there is one proton per electron (i.e. no pairs), then P_p for FSRQs is a factor ~ 10 – 100 larger than P_r , meaning an efficiency of 1–10% for the jet to convert its bulk kinetic motion into radiation (see the right panel of Fig. 6). This is reasonable: most of the jet power in FSRQs goes to form and energize the large radio structures, and not into radiation.

We then conclude that *jets should be matter dominated*, at least at the scale (hundreds of Schwarzschild radii from the black hole) where most of their luminosity is produced. The bottom left panel of Fig. 6 shows the distribution of the disk luminosities. In this case the shaded area corresponds to upper limit for BL Lac objects, and not to actual values. This L_d distribution lies at intermediate values between P_r and P_p .

6 The jet–disk connection

Fig. 7 shows P_r (left) and $P_{\text{jet}} \equiv P_p + P_e + P_B$ (right) as a function of the thermal disk luminosity L_d . Arrows correspond to BL Lacs for which only an upper limit on L_d could be derived. The different symbols correspond to blazars of different γ -ray luminosities, and one can see that L_γ correlates both with P_{jet} and L_d . Furthermore we also show blazars not yet detected by *Fermi*, but present in the all sky survey of *Swift*/BAT, and lying at $z > 2$. As discussed in G10, there is a significant correlation between P_{jet} and L_d for FSRQs, which remains highly significant even when excluding the common redshift dependence. The slope of this correlation for FSRQs is consistent with being linear, with P_{jet} slightly larger than L_d . For BL Lacs $P_{\text{jet}} \gg L_d$, but for the majority of BL Lacs we can estimate only an upper limit on L_d , so the slope of the relation (if any) $P_{\text{jet}}-L_d$ is not known.

The grey stripe is indicative of what expected if P_{jet} always traces \dot{M} (irrespective of the accretion

regime, ADAF or radiatively efficient), while $L_d \propto \dot{M}^2$ at low luminosity, and $L_d \propto \dot{M}$ above some critical value, marking the passage from radiatively inefficient to efficient disk. If true, this implies that

$$\begin{aligned} P_{\text{jet}} &= k L_d, & L_d > L_c \\ P_{\text{jet}} &= k (L_d L_c)^{1/2}, & L_d < L_c \end{aligned} \quad (3)$$

where k should be of order of (but somewhat larger than) unity. The critical luminosity should be of the order of $L_c \sim 10^{-2} L_{\text{Edd}}$, corresponding to $\dot{M}_c \sim 0.1 \dot{M}_{\text{Edd}}$.

Limiting ourselves to FSRQs, we can conclude that the jet power is proportional to the mass accretion rate, but it can be even greater than the accretion luminosity. 3C 454.3, during major flares, showed $P_d > L_d$, and note that P_r is a very robust *lower limit* to P_{jet} . The proportionality between P_{jet} and L_d call for an important role of accretion in powering jets, but the fact that P_{jet} can be larger than the disk luminosity makes this possibility very unlikely. This paradox can be solved in two ways.

Jets powered by accretion only — Jolley et al. (2009, see also Jolley & Kuncic 2008), propose that, in jetted sources, a sizable fraction of the accretion power goes to power the jet. As a result, the remaining power for the disk luminosity is less than usually estimated by setting the efficiency $\eta \sim 0.08$ – 0.1 . This implies a larger mass accretion rate to sustain L_d . The total gravitational energy produced by the mass accretion rate, with total efficiency $\eta = \eta_d + \eta_{\text{jet}}$ goes only in part to produce the disk luminosity (with efficiency η_d), while the rest (with efficiency η_{jet}) goes to power the jet. Our results would require $\eta_{\text{jet}} > \eta_d$.

Jets powered by the black hole spin — The rotational energy of a maximally spinning black hole is large: $0.29 M c^2$ (i.e. $5 \times 10^{62} M_9$ erg). However, this huge reservoir of energy, amply sufficient to power a strong jet for its entire lifetime, must be extracted at a sufficiently rapid pace. The observed relation between L_d and P_{jet} can be explained by linking the extraction of the hole rotational energy to the accretion process. The idea is that, as in Blandford & Znajek (1977) process, there must be a magnetic field to tap the rotational hole energy. This magnetic field must be produced by the disk, therefore by accretion. In this case the accretion rate enters because it produces the catalyzer of the process. The maximum magnetic field that a disk can sustain will have an energy density of the order of the gravitational energy of the matter (if larger, it would disrupt the disk). Therefore $B^2/(8\pi) \sim \rho v_\psi^2$ (v_ψ is the Keplerian velocity of the matter in the disk). The total efficiency of the process has been debated in recent years (e.g. Moderski & Sikora 1996; Ghosh & Abramowicz 1997; Livio, Ogilvie & Pringle 1999; McKinney 2005; Garofalo 2009; Krolik & Hawley 2002), and is not yet clear if the Blandford & Znajek process can indeed account for the huge powers that γ -loud jets are demanding.

7 Summary and conclusions

Understanding extragalactic relativistic jets is not an easy task: after almost half a century since their discovery we still do not know what produces and collimates them. On the other hand our knowledge of jets has steadily increased over the years, with the most recent advances obtained through γ -ray observations, disclosing the jet emission where it peaks. Besides the high energy observations, the other key quantities that start to be known for several relativistic jets is the mass of the black hole and the mass accretion rate of their disks. This allows to measure quantities in Eddington units and to compare the jet powers with the accretion luminosities. The key results are:

- The radiative jet power, $P_r = L_{\text{bol}}/\Gamma^2$ is a lower limit of the jet power, and is model-independent (apart from the value of Γ).
- Jets cannot be magnetically dominated, at least at the scale where they produce most of the emission ($\sim 10^3$ Schwarzschild radii). If there is one proton per emitting particle, then $P_{\text{jet}} \sim (10\text{--}100) \times P_r$.
- In powerful FSRQs, the optical-UV flux can be produced by the accretion disk. In these blazars we can then measure the black hole mass and the accretion rates. The comparison of the mass inferred by fitting a standard disk spectrum with the mass derived by other methods is reassuring.
- Jets are produced for all accretion rates measured in Eddington units.

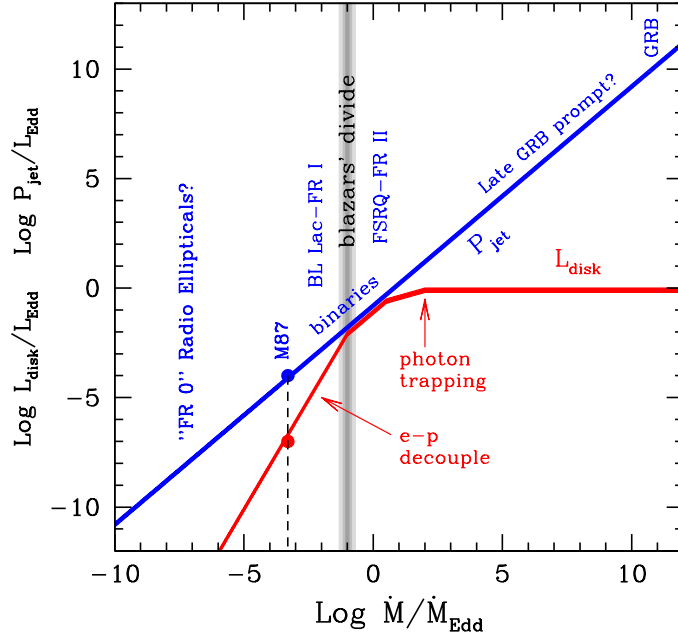


Figure 8: Sketch illustrating P_{jet} and L_d as a function of $\dot{M}/\dot{M}_{\text{Edd}}$. It is assumed that the jet power always scales linearly with \dot{M} , while accretion rates below a critical value produce radiatively inefficient accretion disks. In this case the object looks like a BL Lac (if aligned) or a FR I (if misaligned). The grey stripe indicates the critical $\dot{M}/\dot{M}_{\text{Edd}} \sim 0.1$, producing the blazars' divide at $L_d/L_{\text{Edd}} \sim 10^{-2}$ equivalent to $\dot{M}/\dot{M}_{\text{Edd}} = 0.1$. At very high $\dot{M}/\dot{M}_{\text{Edd}}$ we find GRBs. Apart from their proper prompt emission, in which they emit γ -rays, there is a phase (lasting a few hours) of X-ray emission (with flares super-imposed) that has been interpreted as due to the central engine, but accreting a smaller (and decreasing rate). This phase is labeled “Late GRB prompt?”. The “FR 0” radio ellipticals are a new population of radio sources (Baldi et al. 2009) having the same core radio luminosity of FR Is, but hundreds of times less power in the extended emission.

- The different “look” of BL Lacs and FSRQs could be the result of a different environment, in turn dependent on the accretion regime of the accretion disk. This leads to a new classification scheme, dividing BL Lacs and FSRQs on the basis of the value of $L_{\text{BLR}}/L_{\text{Edd}}$ smaller or greater than $\sim 10^{-3}$ (corresponding roughly to $L_d/L_{\text{Edd}} \sim 10^{-2}$).
- The jet power correlates with the luminosity of the accretion.
- Fig. 8 shows schematically how the power of jets and the accretion luminosity could be related to \dot{M} in Eddington units. This allows to properly compare objects with different black hole masses, such as, besides radio-loud AGNs, Galactic X-ray binaries and Gamma Ray Bursts. The jet power could be *always* proportional to \dot{M} . The disk luminosity, instead, is reduced at both ends of $\dot{M}/\dot{M}_{\text{Edd}}$, by the decoupling between electron and protons (at the low end) and by photon trapping (at the high end). Blazars (and radio-galaxies) have a continuity in the power of their jets, but the different accretion regimes create a discontinuity in environment: above $\dot{M}/\dot{M}_{\text{Edd}} = 0.1$ (equivalent to $L/L_{\text{Edd}} = 10^{-2}$) the disk is “standard”, photoionizes the clouds of the BLR and can illuminate a dusty IR torus. The environment is therefore rich in seed photons that the jet emitting region can scatter to high energies. The radiative cooling is severe, the typical electron energies are relatively small, and the overall SED peaks in the far IR and in the MeV bands. Below $\dot{M}/\dot{M}_{\text{Edd}} = 0.1$ the disk becomes radiatively inefficient and the photoionizing flux is largely reduced, the emission lines becomes weak or absent.

Radiative cooling is less severe, electrons can reach large energies, producing a SED peaking in the UV (or X-ray) and in the GeV (or TeV) bands. The critical, dividing, value of $\dot{M}/\dot{M}_{\text{Edd}}$ translates into the “divide” between BL Lacs and FSRQs. Fig. 8 shows also the location of other class of jetted sources in the same plane. Galactic binaries, when producing a jet, should lie in the same region of blazars, while Gamma Ray Bursts, having $\sim 10^{12}$ Eddington luminosities, are at the extreme top right of the plane. The figure reports also the location of M87, a nearby radio-galaxy (TeV emitting) thought to be a misaligned blazar, with a radiatively inefficient accretion disk. Finally, Fig. 8 shows the predicted location of the newly discovered population of weak radio-galaxies (Baldi et al. 2009) with core radio luminosities similar to FR I sources, but with an extended emission hundreds of times weaker, that we call “FR 0”.

- Blazars are powerful, and therefore we can detect them up to large distances. Moreover, in powerful blazars the non-thermal SED leaves unhidden the disk emission, allowing us to measure their black hole mass. As a consequence *we can find heavy black holes at large redshifts*. For each detected blazar, there must be a few hundreds of similar sources pointing in other directions. These simple considerations imply that the search for young (i.e. high redshift) and heavy (i.e. $M > 10^9 M_\odot$) black holes can largely benefit from blazars. Limits on the mass function (for $M > 10^9 M_\odot$) at $z \gtrsim 4$ derived from the radio loud population are comparable (Volonteri et al. 2011) with those derived from the SDSS (radio-quiet) quasars (i.e. Hopkins et al. 2007).

It can be instructive to conclude this review by pointing out some of the problematic issues that could be solved in the near future (this is a subjective choice...).

- *One or two (or more) subclasses of blazars?* — We have up to now divided blazars into BL Lacs and FSRQs, further subdividing BL Lacs according to where their SED peaks (HBL, LBL, IBL, Padovani & Giommi 1995) and FSRQs according to if they are lobe or core dominated or if they have a high level of optical polarization or not (HPQ, LPQ). But the new results coming from γ -rays suggest that the key quantities, besides orientation, controlling how these subclasses of radio-loud sources look like are the power of their jets and the strength of their accretion disks. It may be more productive to think to radio-sources as a single population, that appears different, but has instead the same basic jet structure. One example: for many years we discussed the cosmic evolution properties of BL Lacs and FSRQs separately, while now a unified approach may be more fruitful (in line with Maraschi & Rovetti 1994; Cavaliere & D’Elia 2002).
- *A one-zone simple model?* — A single-zone model is certainly a crude simplification. After all we do see several knots in the radio jets, so we do know that some emission come from different structures in the jet. At the same time, this simplification allowed a huge step in our understanding of the basic physics of the jet emission. What remains to be done is to assess the importance of additional emission regions. Can they become sometimes dominant? In what frequency ranges? Are they really necessary to understand the physics of jets or are they “second order” effects? An example: the detection of radio-galaxies both by *Fermi* (Abdo et al. 2010b) and by Cherenkov telescopes (e.g. M87: Aharonian et al. 2004; CenA: Aharonian et al. 2009; NGC 1275: Mariotti et al. 2010; IC 310: Aleksić et al. 2010) would be difficult to understand by assuming an emission region moving with a very large bulk Lorentz factor, and points to a more structured jet (e.g. a decelerating flow as in Georganopoulos & Kazanas 2003; a spine/layer as in Ghisellini et al. 2005 and in Tavecchio & Ghisellini 2008 or a reconnection region as Giannios et al. 2009b).
- *Ultrafast TeV variability* — This is related to the previous issue, as it must be produced by a very small region, possibly moving with a very large Γ . The novelty in this field is the detection of 10 minutes flux variation in a FSRQs with broad lines (in 1222+216, Aleksić et al. 2011). So this phenomenon occurs not only in “classical” low power TeV BL Lacs, but also in powerful sources (see Tavecchio et al. 2011, in prep, for a discussion of possible models).
- *Relativistic jets in Galactic binaries* — Are they a scaled down version of extragalactic jets? If so, there is a lot to learn from these sources, because they can give us a “movie” of the entire lifetime of the jet (i.e. one year in the life of a jetted Galactic binary is equivalent to $\sim 10^8$ years of a jetted

AGN). The recent detection of Cyg X-3 by *AGILE* and *Fermi* (Tavani et al. 2009; Corbel et al. 2010) is intriguing.

- *Role of the black hole spin* — This is a long standing issue, so it should be prudent to think to a solution of this issue not in the immediate future, but on a longer timescale. On the other hand there have been in the recent literature many studies aiming to estimate the black hole spin in jetted sources (among others: Fender et al. 2010; Daly 2009; McClintock et al. 2010). While not conclusive, they are the first attempts to solve this issue experimentally (i.e. observationally), and this line of research could improve considerably.

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References

- [1] Abdo A.A., Ackermann M., Ajello M. et al., 2009, ApJ, 700, 597 (A09)
- [2] Abdo A.A., Ackermann M., Ajello M. et al., 2010a, ApJ, 715, 429 (A10)
- [3] Abdo A.A., Ackermann M., Ajello M. et al., 2010b, ApJ, 720, 912
- [4] Abdo A.A., Ackermann M., Ajello M. et al., 2011, ApJ, in press, (astro-ph/1102.0277)
- [5] Aharonian F.A., 2000, New Astronomy, 5, 377
- [6] Aharonian F.A., Akhperjanian A.G., Beilicke M. et al. 2004, A&A, 421, 529
- [7] Aharonian F.A., Akhperjanian A.G., Razer-Bachi A.R. et al., 2007, ApJ, 664, L71
- [8] Aharonian F.A., Akhperjanian A.G., Anton, G. et al. 2009, ApJ, 695, L40
- [9] Ajello M., Costamante L., Sambruna R. et al., 2009, ApJ, 699, 603
- [10] Albert J., Aliu E., Anderhub H. et al., 2007, ApJ, 669, 862
- [11] Aleksic J., Antonelli L.A., Antoranz P. et al., 2011, ApJ, 723, L207
- [12] Aleksic J., Antonelli L.A., Antoranz P. et al., 2010, ApJ, 730, L8
- [13] Allen S.W., Dunn R.J.H., Fabian A.C., Taylor G.B. & Reynolds C.S., 2006, MNRAS, 372, 21
- [14] Baldi R.D. et al., 2009, A&A, 508, 603.
- [15] Balmaverde B. et al., 2008, A&A, 486, 119
- [16] Begelman M.C., Fabian A.C. & Rees M.J., 2008, MNRAS, 384, L19
- [17] Bentz M.C., Peterson B.M., Netzer H., Pogge R.W. & Vestergaard M., 2009, ApJ, 697, 160
- [18] Blandford R.D. & Znajek R.L., 1977, MNRAS, 179, 433
- [19] Bloom S.D. & Marscher A.P. 1996, ApJ, 461, 657
- [20] Bonnoli G., Ghisellini G., Foschini L, Tavecchio F., Ghirlanda G., 2011, MNRAS, 410, 368
- [21] Böttcher M., 2007, Ap&SS, 309, 95
- [22] Burbidge, G.R., 1959, ApJ, 129, 849
- [23] Cavaliere A. & D’Elia V., 2002, ApJ, 571, 226

- [24] Celotti A., Ghisellini G., & Chiaberge M., 2001, MNRAS, 321, L1
- [25] Celotti A., Padovani P., & Ghisellini G., 1997, MNRAS, 286, 415
- [26] Celotti A. & Ghisellini G., 2008, MNRAS, 385, 283
- [27] Corbel S. & Diderot P., 2010, ATel n. 2611
- [28] Daly R.A., 2009, ApJ, 691, L72
- [29] Dermer C.D. & Schlickeiser R., 1993, ApJ, 416, 458
- [30] Dermer C.D., Cavadini M., Razzaque S., Justin D., Finkel J.D. & Lott B., 2011, ApJ, in press, (astro-ph/1011.6660)
- [31] Donato D., Ghisellini G., Tagliaferri G. & Fossati G., 2001, A&A, 375, 739
- [32] Fender R.P., Gallo E. & Russell D., 2010, MNRAS, 406, 1425
- [33] Foschini L., Ghisellini G., Tavecchio F., Bonnoli G., 2011, MNRAS subm.
- [34] Fossati G., Maraschi L., Celotti A., Comastri A. & Ghisellini G., 1998, MNRAS, 299, 433
- [35] Garofalo D., 2009, ApJ, 699, 400
- [36] Georganopoulos M., Kazanas D., Perlman E. & Stecker F.W., 2005, ApJ, 625, 656
- [37] Georganopoulos M. & Kazanas D., 2003, ApJ, 594, L27
- [38] Ghisellini G., Celotti A., Fossati G., Maraschi L. & Comastri A., 1998, MNRAS, 301, 451
- [39] Ghisellini G., 1999, Astronomische Nachrichten, 320, 232
- [40] Ghisellini G. & Celotti A., 2001, A&A, 379, L1
- [41] Ghisellini G., Tavecchio F. & Chiaberge M., 2005, A&A, 432, 401
- [42] Ghisellini G. & Tavecchio F., 2008, MNRAS, 387, 1669
- [43] Ghisellini G. & Tavecchio F., 2009, MNRAS, 397, 985
- [44] Ghisellini G., Maraschi L. & Tavecchio F., 2009, MNRAS, 396, L105 (GMT09)
- [45] Ghisellini G., Foschini L., Volonteri M., Ghirlanda G., Haardt F., Burlon D., Tavecchio F. 2009, MNRAS, 399, L24
- [46] Ghisellini G., Tavecchio F., Bodo G., Celotti A., 2009, MNRAS, 393, L16
- [47] Ghisellini G., Tavecchio F., Foschini L., Ghirlanda G., Maraschi L. & Celotti A., 2010a, MNRAS, 402, 497 (G10)
- [48] Ghisellini G., Della Ceca R., Volonteri M. et al., 2010b, MNRAS, 405, 387
- [49] Ghisellini G. & Tavecchio F., 2010, MNRAS, 409, L79
- [50] Ghisellini G., Tavecchio F., Foschini L., Ghirlanda G., 2011, MNRAS in press
- [51] Ghosh P. & Abramowicz M.A., 1997, MNRAS, 292, 887
- [52] Giannios D., Uzdensky D.A. & Begelman M.C., 2009a, MNRAS, 395, L29
- [53] Giannios D., Uzdensky D.A. & Begelman M.C., 2009b, MNRAS, 402, 1649
- [54] Guetta D., Ghisellini G., Lazzati D., Celotti A., 2004, A&A, 421, 877

- [55] Hartman R.C., Bertsch D.L., Bloom S.D., 1999, *ApJS*, 123, 79
- [56] Hopkins P.F., Hernquist L., Cox, T.J., Robertson B. & Krause E., 2007, *ApJ*, 669, 67
- [57] Jolley E.J.D. & Kuncic Z., 2008, *MNRAS*, 386, 989
- [58] Jolley E.J.D., Kuncic Z., Bicknell G.V. & Wagner S., 2009, *MNRAS*, in press (astro-ph/0908.2337)
- [59] Kaspi S., Brandt W.N., Maoz D., Netzer H., Schneider D.P. & Shemmer O., 2007, *ApJ*, 659, 997
- [60] Kataoka J., Madejski G., Sikora M., et al., 2008, *ApJ*, 672, 787
- [61] Krolik J.H. & Hawley J.F., 2002, *ApJ*, 573, 754
- [62] Livio M., Ogilvie G.I. & Pringle J.R., 1999, *ApJ*, 512, 100
- [63] Mahadevan R., 1997, *ApJ*, 477, 585
- [64] Mannheim K., 1993, *A&A*, 269, 67
- [65] Maraschi L., Ghisellini G. & Celotti A., 1992, *ApJ*, 397, L5
- [66] Maraschi L. & Rovetti F., 1994, *ApJ*, 436, 79
- [67] Maraschi L. & Tavecchio F., 2003, *ApJ*, 593, 667
- [68] Mariotti M. for the MAGIC collaboration, 2010, *ATel*, n. 2916
- [69] Mazin D. & Raue M., 2007, *A&A*, 471, 439
- [70] McClintock J.E., Narayan R., Davis S.W. et al., 2010, *Classical and Quantum Gravity*, in press (astro-ph/1101.0811)
- [71] McKinney J.C., 2005, *ApJ*, 630, L5
- [72] Moderski R. & Sikora M., 1996, *MNRAS*, 283, 854
- [73] Mücke A. & Protheroe R.J., 2001, *Astroparticle Physics*, 15, 121
- [74] Mücke A., Protheroe R.J., Engel R., Rachen J.P. & Stanev, T., 2003, *Astroparticle Physics*, 18, 593
- [75] Nandikotkur G., Jahoda K.M., Hartman R.C., Mukherjee R., Sreekumar P., Böttcher M., Sambruna, R.M.; Swank J.H., 2007, *ApJ*, 657, 706
- [76] Narayan R., Garcia M.R. & McClintock J.E., 1997, *ApJ*, 478, L79
- [77] Neronov A. & Vovk I., 2010, *Science*, 328, 73
- [78] Padovani P. & Giommi P., 1995, *ApJ*, 444, 567
- [79] Padovani P., Perlman E.S., Landt E., Giommi P. & Perri M., 2003, *ApJ*, 588, 128
- [80] Pian E., Vacanti G., Tagliaferri G. et al., 1998, *ApJ*, 492, L17
- [81] Rawlings S.G. & Saunders R.D.E., 1991, *Nature*, 349, 138
- [82] Sambruna R.M., Gliozzi M., Tavecchio F. et al., 2006, *ApJ*, 652, 146
- [83] Scarpa R. & Falomo R., 1997, *A&A*, 325, 109
- [84] Shakura N.I. & Sunyaev R.A., 1973, *A&A*, 24, 337
- [85] Sikora M., Begelman M.C. & Rees M.J., 1994, *ApJ*, 421, 153
- [86] Sikora M. & Madejski G., 2000, *ApJ*, 534, 109

- [87] Sikora M., Błazejowski M., Moderski R. & Madejski G.M., 2002, *ApJ*, 577, 78
- [88] Spada, M., Ghisellini, G., Lazzati, D. & Celotti, A., 2001, *MNRAS*, 325, 1559
- [89] Tavani M., Bulgarelli A., Piano G. et al., 2009, *Nature*, 462, 620
- [90] Tavecchio F., Maraschi L., Sambruna R.M. & Urry C.M., 2000, *ApJ*, 544, L23
- [91] Tavecchio F. & Ghisellini G., 2008, *MNRAS*, 385, L98
- [92] Tavecchio F., Ghisellini G., Ghirlanda G., Bonnoli G., 2010, *MNRAS*, 405, L94
- [93] Tavecchio F., Ghisellini G., Foschini L., Bonnoli G., Ghirlanda G., Coppi P., 2010, *MNRAS*, 406, L94
- [94] Tavecchio F., Ghisellini G., Bonnoli G. & Foschini L., 2011, *MNRAS*, in press
- [95] Urry C.M & Padovani P., 1995, *PASP*, 107, 803
- [96] Volonteri M., Haardt F., Ghisellini G. & Della Ceca R., 2011, *MNRAS*, *subm.*